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2. Patent application number *(The Patent Office will fill in this part)* — 25 OCT 2002 — 0224911.8

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

   Council for the Central Laboratory of the Research Councils
   Rutherford Appleton Laboratory
   Chilton
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   Oxfordshire
   OX11 0QX

   06767131001
   Patents ADP number *(if you know it)*

   If the applicant is a corporate body, give the country/state of its incorporation — United Kingdom

4. Title of the invention — TUNEABLE PHASE SHIFTER

5. Name of your agent *(if you have one)* — STEVENS HEWLETT & PERKINS

   "Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

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Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

7. If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application

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8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:*
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Description	11
Claim *(s)*	1
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11. I/We request the grant of a patent on the basis of this application.

Signature Stevens Hewlett & Perkins Date 25/10/02

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TUNEABLE PHASE SHIFTER

The present invention relates to a phase shifter and in particular to an optically tuneable phase shifter capable of operating in the terahertz spectrum. The phase shifter may be used in a wide range of applications including, but not limited to, phase-shift-keying circuitry, terahertz imaging, terahertz transceivers and phased-array antennas.

In the past, terahertz technology been primarily been used in the fields of terrestrial and astronomical remote sensing. However, many materials that are opaque in the optical and infrared regions are transparent to terahertz waves (0.1 THz to 10 THz). Applications for terahertz technology have thus recently expanded to include areas such as aerial navigation where terahertz waves are able to penetrate clouds and fog, medical imaging where body tissue can be examined without using potentially harmful ionising radiation, and non-invasive security systems for use at airports and ports in which the terahertz waves are able to pass through clothing and materials normally opaque to infrared.

Owing to the sub-millimetre wavelengths of terahertz waves, the required dimensions and accuracy of components such as antennas, waveguides, lenses, mirrors etc. make fabrication difficult and costly using conventional manufacturing techniques.

In the millimetre waveband, ferroelectric phase shifters are often employed in which the phase of the signal is shifted by varying the permitivity of the ferroelectric material by means of an applied electric field. Unfortunately, ferroelectric phase shifters suffer from substantial power losses, signal distortions and noise.

It is therefore an object of the present invention to provide a tuneable phase shifter capable of operating at sub-millimetre wavelengths which overcomes in part one or more of the aforementioned disadvantages of the prior art.

Accordingly, the present invention provides a tunable phase shifter, comprising a waveguide having an aperture formed in a side of the waveguide and a photo-responsive material disposed within the waveguide so as to extend substantially across the aperture, wherein a photo-induced reflective region is formed in the photo-responsive material upon exposure to optical irradiation.

The photo-responsive material is transparent to radiation having sub-millimetre wavelengths in the absence of optical irradiation and suitable materials include, but are not limited to, Si, GaAs or Ge.

In order to extend the lifetime of the photo-induced reflectivity region, the photo-responsive material preferably has a high electrical resistivity and the surface of the photo-responsive material facing the aperture is pacified, e.g. by oxidation.

The phase shifter may also include at least one reflecting element disposed on the surface of the photo-responsive material facing the aperture. The reflecting element serves to reflect radiation propagating through the waveguide in the absence of any photo-induced reflective region. The reflecting element is preferably a plurality of metal strips which extend across the surface of the photo-responsive material facing the aperture.

Embodiments of the present invention will now be described by way of example with reference to the accompanying drawings, in which:

Figure 1 is a schematic cross-sectional view of a tuneable phase shifter in accordance with the present invention;

Figure 2 is a schematic cross-sectional view of a tuneable phase shifter in accordance with the present invention taken along the line A-A in Figure 1;

Figure 3 is a schematic cross-sectional view of radiation propagating through a tuneable phase shifter in accordance with the present invention; and

Figure 4 is a further schematic cross-sectional view of radiation propagating through a tuneable phase shifter in accordance with the present invention.

The tuneable phase shifter 10 illustrated in Figures 1 and 2 comprises a waveguide 11 having a central channel 12 which extends the length of the waveguide 11 and an aperture formed in a side 13 of the waveguide 11. The tuneable phase shifter 10 further comprises a photo-responsive reflector 18 disposed within the channel 19 of the waveguide 12 so as to extend substantially across the aperture. An irradiation source 14 is located outside the waveguide such that irradiating radiation from the source 14 is incident upon an area of the photo-responsive reflector 18 exposed by the aperture formed in the side 13 of the waveguide 11.

The waveguide 11 comprises a silicon body 15 having a central channel 12 substantially rectangular in cross-section extending the length of the silicon body 15. The silicon body 15 is preferably dimensioned such that the width of the channel 12 is twice that of the height, as is conventionally employed in rectangular waveguide construction. However, the dimensions of the silicon body 15 may be adjusted according to preference.

The inner surfaces 16 of the silicon body 15 are coated with a metallic film 17, preferably using vacuum deposition and electroplating techniques. However, other coating techniques may alternatively be used. Suitable metals for coating the silicon body 15 include, but are not limited to, nickel, copper, brass, chromium, silver and gold. The metal coating 17 acts to reflect radiation propagating along the length of the channel 12. Accordingly, the coating 17 may comprise any material which serves to reflect radiation at terahertz frequencies.

The construction of metallised silicon waveguides for terahertz applications using micromachining techniques is known and is described for example in "Silicon Micromachined Waveguides for Millimeter and Submillimeter Wavelengths", Yap et al., Symposium Proceedings: Third

International Symposium on Space Terahertz Technology, Ann Arbor, MI, pp. 316-323, March 1992 and "Micromachining for Terahertz Applications", Lubecke et al., IEEE Trans. Microwave Theory Tech., Vol. 46, pp. 1821-1831, Nov. 1998.

The aperture formed in the side 13 of the waveguide 11 extends through the silicon body 15 and the metal coating 17 on one of the longer sides of the waveguide 11. The aperture is preferably rectangular in shape and has a width substantially similar to the width of the channel 12. The length of the aperture is characterised by the desired degree of phase shifting. Generally speaking, the longer the length of the aperture (or rather the longer the exposed region of the photo-responsive reflector 18), the greater the degree of phase shifting. The length of the aperture is preferably at least ten times the wavelength of the radiation propagating along the channel 12 of the waveguide 11.

The photo-responsive reflector 18 comprises a layer of photo-responsive responsive material 19 and a plurality of reflective elements 20. The layer of photo-responsive material 19 has an upper 21 and lower 22 surface substantially rectangular in shape. The width of the layer 19 is substantially similar to the width of the channel 12, whilst the length of the layer 19 is preferably longer than the length of the aperture formed on the side 13 of the waveguide 11. Preferably the length of the layer 19 is only slightly longer than that of the aperture. The layer 19 is secured within the channel 12 of the waveguide 11 such that the layer 19 extends substantially across the aperture formed in the side 13 of the waveguide 11. The layer of photo-responsive material 19 is secured to a wall 23 of the channel 12 by a thin layer of adhesive applied at the ends 24,25 of the layer 19 extending beyond the length of the aperture.

The photo-responsive material 19 is constructed of a material which is transparent to radiation having terahertz frequencies. Furthermore, the photo-responsive material is capable of photo-induced reflectivity, i.e. the reflectivity of the material varies in response to incident radiation at visible

or infrared wavelengths. The photo-responsive material 19 preferably consists substantially of intrinsic silicon. However, alternative photo-responsive materials which may be used include, but are not limited to, GaAs and Ge.

When the optical radiation is incident upon the exposed surface 21 of the photo-responsive material 19, photo-excited carriers are created at a region near the surface 21. Accordingly, the reflectivity of the photo-responsive material 19 in this region increases; generally referred to as photo-induced reflectivity. The reflectivity of the irradiated surface 21 of the photo-responsive material 19 can be rendered similar to that of a metal in dependence upon the intensity of the incident optical radiation. At this point, the photo-responsive material 19 can be regarded as having a separate photo-induced reflective layer (reference numeral 26 in Figure 4) having a reflectivity comparable to a metal. The thickness of this photo-induced reflective layer depends upon the frequency and intensity of the optical radiation delivered by the irradiation source 14. Nevertheless, the increase in thickness of the photo-induced reflective layer with increasing incident radiation intensity drops off rapidly. For silicon, this generally occurs at a depth of around 60 μm.

Whilst the photo-responsive material 19 is generally transparent to the radiation propagating along the channel 12 of the waveguide 11, some power loss of the signal will occur. Accordingly, the thickness of the layer of photo-responsive material 19 preferably does not exceed 100 μm, and is preferably between 60 and 100 μm. Moreover, the photo-responsive material 19 is preferably silicon having a thickness of 70 μm.

The lifetime of the photo-excited carriers are determined primarily by their mobility and the availability of recombination sites in the lattice of the photo-responsive material 19. By increasing the lifetime of the carriers, the lifetime of the photo-induced reflective layer can be extended. Accordingly, the irradiation delivered by the source 14 may be delivered over shorter periods of time. Not only does this reduce the amount of power consumed

by the irradiation source but it also prevents the photo-responsive material 19 from reaching potentially damaging temperatures which can arise from continuous irradiation. In order to increase the lifetime of the carriers, the photo-responsive material 19 preferably has a high electrical resistivity (> 1 $k\Omega cm^{-2}$). The photo-responsive material 19 preferably consists essentially of silicon having an electrical resistivity of between 4 and 9 $k\Omega cm^{-2}$.

Moreover, the lifetime of the carriers can be further increased by pacifying the irradiated surface 21 of the photo-responsive material 19. The surface 21 of the photo-responsive material 19 offers a large number of recombination sites. By pacifying the irradiated surface 21, the number of recombination sites available to the carriers is significantly reduced. The uppermost surface 21 of the photo-responsive material is therefore preferably oxidised. Even with oxidation, however, the number of recombination sites remains sufficiently high to significantly affect the mobility of carriers. It has been found, however, that by applying a coating of an adhesive such as an epoxy resin to the oxidised surface of the photo-responsive material can significantly increased carrier lifetime.

In having a photo-responsive material 19 comprising essentially of high resistance silicon with a resistivity of between 4 and 9 $k\Omega cm^{-2}$ and an oxidised upper surface coated in an epoxy resin, the lifetime of the photo-induced carriers and thus the photo-induced reflective layer is substantially increased. Accordingly, phase shifting may be achieved and maintained with relatively low intensity irradiation. However, in extending the lifetime of the photo-induced carriers, the response time of the phase shifter is increased.

It will, however, be appreciated that fast response times can be achieved by having a photo-responsive material in which the lifetime of the photo-induced carriers is relatively short. This may be achieved, for example, by having a photo-responsive material of low resistance and whose surfaces have not been pacified.

The plurality of reflective elements 20 are formed on the uppermost surface 21 of the photo-responsive material 19 in the region defined by the aperture on the side 13 of the waveguide 11. The reflective elements 20 are preferably strips of material capable of reflecting radiation having terahertz frequencies. Accordingly, the reflective elements 20 are preferably strips of metal. Again, suitable metals include, but are not limited to, nickel, copper, brass, chromium, silver and gold. The strips are preferably aligned on the surface 21 of the photo-responsive material 19 so as to extend substantially parallel to the width of the channel 12 and thus perpendicular to the length of the channel 12. The length of the strips are preferably at least the width of the channel 12 and preferably extend across the full width of the photo-responsive material 19. The strips are evenly spaced along the length of the photo-responsive material 19 and cover around 50% of the region of the surface 21 revealed by the aperture. The width and separation of the strips is preferably no greater than 1 mm. The strips should be of a thickness suitable for total reflection of incident radiation at terahertz frequencies without any substantial loss. The strips may be applied, for example, by applying a mask to the surface 21 of the photo-responsive material 19 and depositing a metal film using vapour deposition.

The irradiation source 14 may be any source capable of generating photo-induced reflectivity in the photo-responsive material 19 and is preferably a commercially-available laser having a visible or near-infrared wavelength. The power required of the source 14 will depend upon, among other things, the type of photo-responsive material 19 and the degree of phase shifting required.

Referring now to Figure 3, radiation propagating along the length of the channel 12 of the waveguide 11 is reflected internally by the surfaces of the metal coating 17. When the radiation is incident upon the photo-responsive reflector 18, the radiation propagates through the photo-responsive material 19 due to its transparent to radiation having terahertz

frequencies. Upon reaching the uppermost surface 21 of the photo-responsive material 19, a substantial proportion of the radiation is reflected back towards the channel 12 by the plurality of reflective elements 20. A small fraction of the radiation is transmitted into the air (indicated by a broken line) and thus exits the waveguide 11. Owing to the angle of incidence of the propagating radiation with respect to the photo-responsive material 19, no internal reflection occurs within the photo-responsive material 19. Accordingly, the radiation reflected by the reflective elements 20 propagates back through the photo-responsive material 19 and into the channel 12. The propagating radiation may be incident upon the photo-responsive reflector 18 more than once, according to the length of the reflector 18, before it continues propagating along with length of the channel 12 of the waveguide 11.

Figure 4 illustrates the situation whereupon irradiating radiation delivered by the irradiation source 14 is incident upon the photo-responsive reflector 18. The irradiating radiation causes a photo-induced reflective layer 26 to form at the surface of the photo-responsive material 19. The thickness or depth of the photo-induced reflective layer 26 will depend upon the wavelength and intensity of the irradiating radiation incident upon the photo-responsive material 19. When the radiation propagating along the channel 12 of the waveguide 11 is incident upon the photo-responsive reflector 18, the radiation propagates through the photo-responsive material 19 only so far as the photo-induced reflective layer 26. Upon reaching the photo-induced reflective layer 26, the propagating radiation is reflected back towards the channel 12. No, or very little, propagating radiation passes through the photo-induced reflective layer 26, though this will depend upon the choice of photo-responsive material and the thickness of the photo-induced reflective layer 26. The propagating radiation now has a phase that is substantially different to radiation propagating along the waveguide 11 in the absence of the photo-induced reflective layer (illustrated in Figure 4 as a broken line). The degree of phase shifting will

depend upon the thickness or depth of the photo-induced reflective layer 26. Furthermore, phase shifting will occur every time the propagating radiation is incident upon the photo-responsive reflector 18. Accordingly, the length of the photo-responsive reflector 18 will also determine the degree of phase shifting. As the thickness or depth of the photo-induced reflective layer 26 is determined by the intensity and wavelength characteristics of the irradiating radiation, the degree of phase shifting can accordingly be controlled by varying the intensity and/or wavelength of the irradiating radiation delivered by the source 14.

The dimensions of the channel 12 of the waveguide 11, the size and characteristics of the photo-responsive reflector 18 and the size of the aperture formed on the side 13 of the waveguide 11 may all be tailored to suit the desired performance of the phase shifter 10. An example of the dimensions that might be used for phase shifting terahertz frequencies is now described. The width and height of the channel 12 is preferably around 1.5 mm and 0.75 mm respectively. This provides a waveguide cut-off frequency of around 0.1 THz. Accordingly, the silicon wafer used to construct the silicon body 15 has a thickness of around 0.75 mm. The metal coating 17 is preferably of the order of 500 nm. The width of the aperture formed on the side 13 of the waveguide is also preferably 0.75 nm. The length of the aperture is preferably around 2 cm. The layer of photo-responsive material 19 preferably has a width, length and thickness of around 0.75 mm, 2.5 cm and 70 μm respectively and has an oxidation layer on the uppermost surface 21 typically or around 10-50 nm. Each reflecting element preferably has a width, length and thickness of around 0.5 mm, 0.75 mm and 500 nm respectively. The spacing between reflecting elements is preferably 0.5 mm.

Whilst the embodiment described above comprises a waveguide having a single aperture and a single photo-responsive reflector 18 extending across the aperture, it will be appreciated that two apertures may be formed on opposing sides of the waveguide 11. Two photo-responsive

reflectors would then be employed and the degree of phase shifting achievable may be doubled. It will be appreciated that the same technical effect might be achieved by doubling the length of the single aperture and photo-responsive reflector 18. Nevertheless, a phase shifter comprising two apertures and two photo-responsive reflectors might be considered when the size, and in particular the length, of the phase shifter is a serious consideration.

It will be appreciated that the plurality of reflecting elements 20 may be omitted from the photo-responsive reflector 18. In this situation, some form of irradiating radiation must be delivered to the photo-responsive reflector 18 such that a photo-induced reflective layer 26 is continuously present. For example, the irradiation source 14 may continuously irradiate the photo-responsive reflector 18 with low intensity radiation. Alternatively, the irradiation source 14 may deliver pulsed, high intensity irradiation.

Rather than forming a plurality of reflective elements 20 on the surface 21 of the photo-responsive material 19 facing the aperture, the reflective elements 20 could be formed on a separate element such as a glass plate. The glass plate could then be placed within the aperture so as to rest on top of the photo-responsive material 19.

The phase shifter 10 may also comprise an attenuator, such as a variable optical attenuator, to compensate for variations in the amplitude of the propagating radiation with phase shift. Moreover, both phase and amplitude modulation of a signal is then possible.

Whilst the phase shifter 10 described herein in is particular well suited for shifting the phase of signals at terahertz frequencies, the phase shifter 10 may also be used to phase shift signals at both higher and lower frequencies, so long as the photo-responsive material is substantially transparent at those frequencies. For example, signals at lower frequencies (e.g. at millimetre wavelengths) require a waveguide having larger dimensions than that for terahertz (sub-millimetre) frequencies. Accordingly, the degree of possible phase shifting is reduced owing to the

reduced ratio of the photo-induced reflective layer thickness with respect to the waveguide height. However, this reduction in phase shifting can be compensated by having a photo-responsive reflector 18 greater in length.

By employing irradiation as the phase shifting signal, phase noise often present with mechanical and electrical phase shifters is greatly reduced. Furthermore, as the photo-responsive material 19 is generally transparent to the propagating signal, signal distortion and power loss is generally low in comparison to ferroelectric phase shifters.

The phase shifter may be used in a wide range of applications including, but not limited to, phase-shift-keying circuitry, terahertz imaging, transceivers and phased-array antennas.

In the case of a phased-array of antennas, each phase shifter is associated with an attenuator which adjusts the amplitude of the mixing signal for the corresponding antenna such that the mixing signals of all antennas have the same amplitude, regardless of the differences in phase phase.

CLAIMS

1. A tunable phase shifter suitable for operating at sub-millimetre wavelengths, the phase shifter comprising a waveguide having an aperture formed in a side of the waveguide and a photo-responsive material disposed within the waveguide so as to extend substantially across the aperture, wherein a photo-induced reflective region is formed in the photo-responsive material upon exposure to optical radiation.

2. The phase shifter as claimed in claim 1, wherein the photo-responsive material is transparent to radiation having sub-millimetre wavelengths in the absence of the optical radiation.

3. The phase shifter as claimed in either one of claims 1 or 2, wherein the photo-responsive material is selected from silicon, GaAs and Ge.

4. The phase shifter as claimed in any one of the preceding claims, wherein the photo-responsive material has an electrical resistivity of at least 4 $k\Omega cm^{-2}$ and at least the surface of the photo-responsive material facing the aperture is pacified.

5. The phase shifter as claimed in any one of the preceding claims, wherein the photo-responsive material has a coating of an epoxy resin on its irradiated surface.

6. The phase shifter as claimed in any of the preceding claims, wherein the phase shifter further comprises at least one reflecting element disposed on the surface of the photo-responsive material facing the aperture.

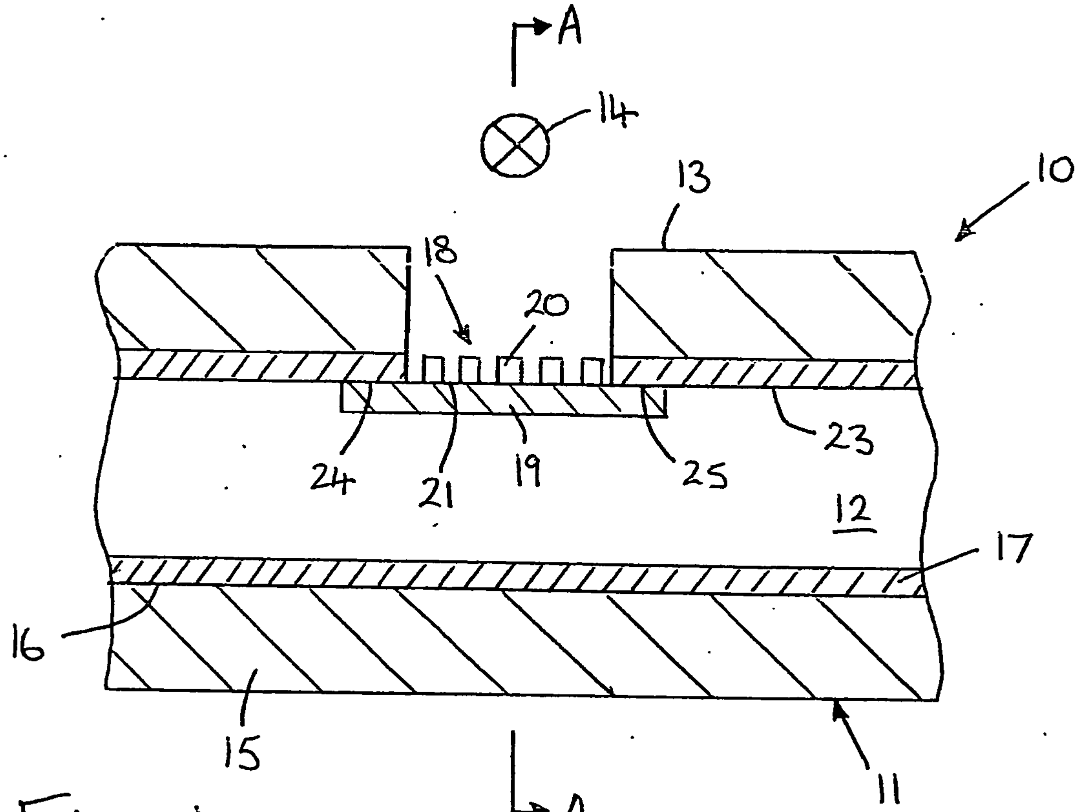
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Fig. 1

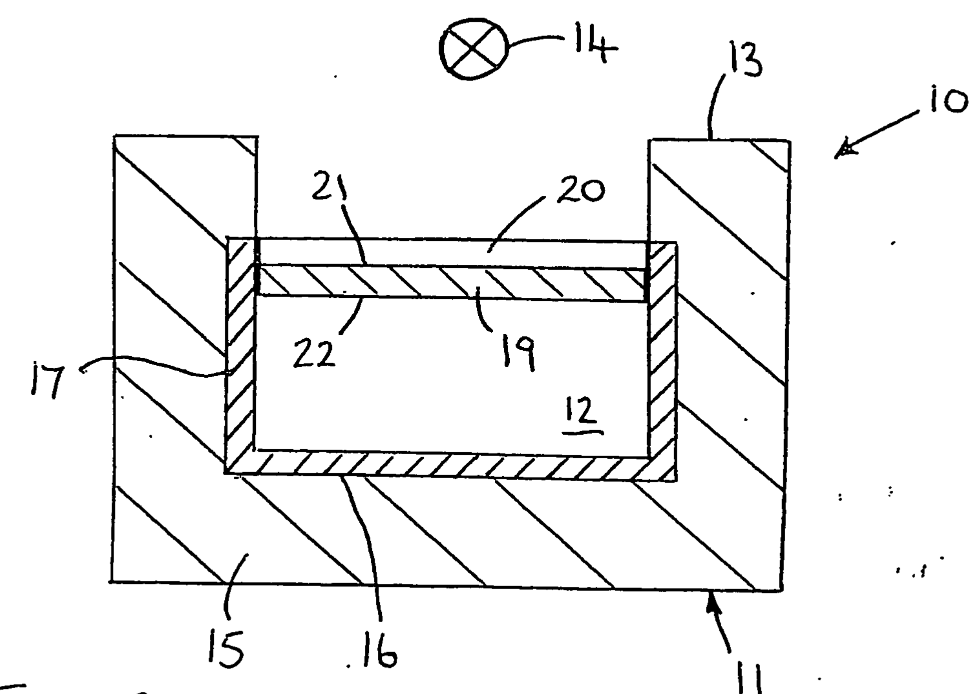
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Fig. 2

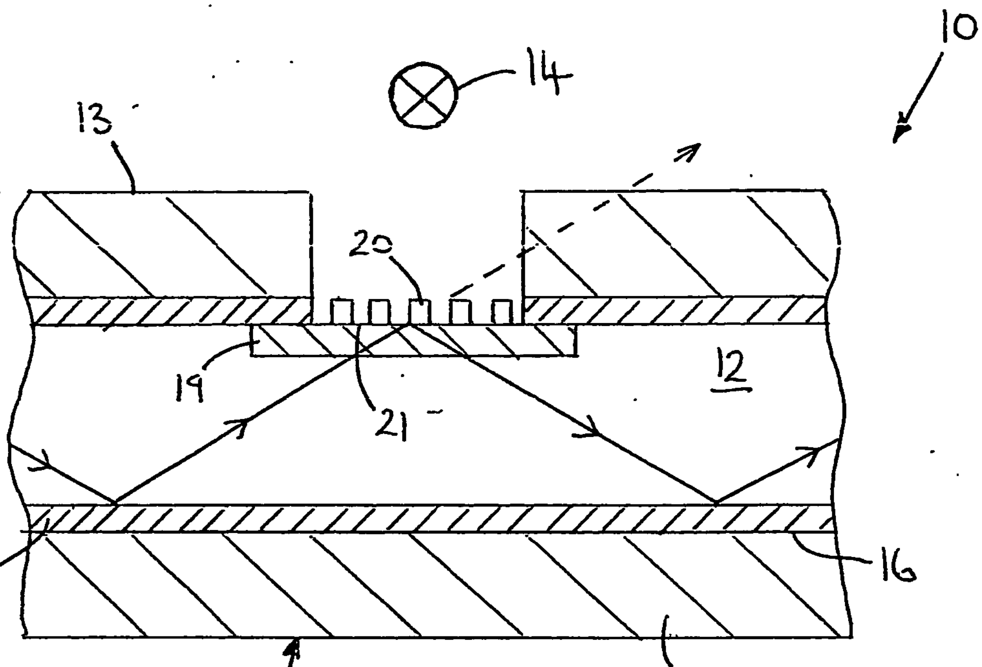

Fig. 3

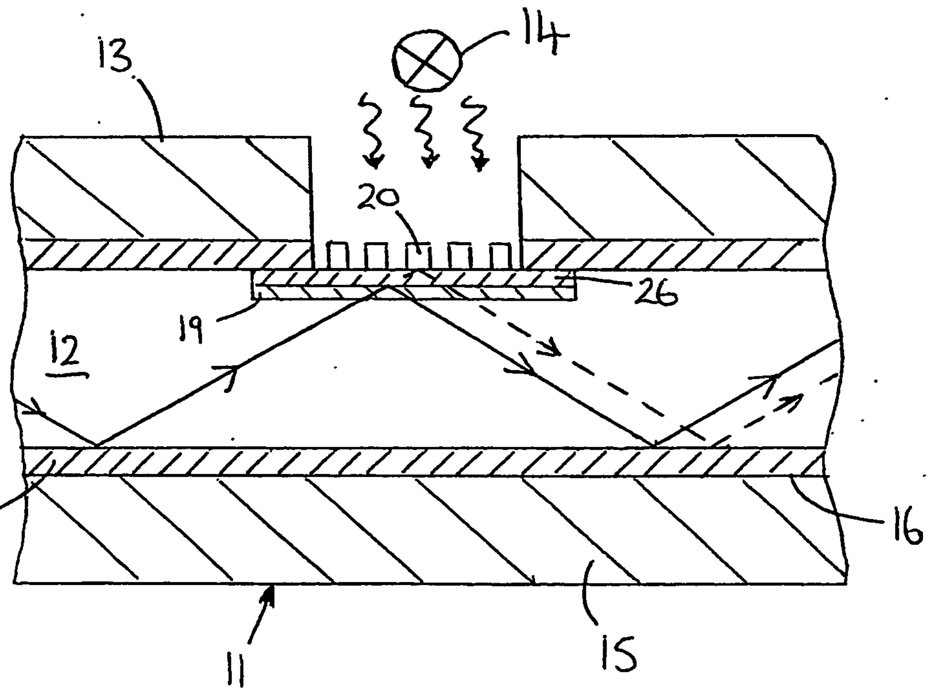

Fig. 4